# 12 Technical Applications

## 12.1 Microelectronics

The applications of superconductivity in microelectronics are essentially based on two facts: magnetic flux quantization and the Josephson effect. In both cases, a macroscopic quantum effect and the description of the state of the Cooper pairs with a quantum mechanical wave function play the central role. A characteristic example is the SQUID (abbreviated from Superconducting Quantum Interference Device). The principle is shown in Fig. 12.1, where two parallel Josephson contacts are built into a closed superconducting loop. Due to magnetic flux quantization, the magnetic flux of an external magnetic field through the loop can only assume values of integer multiples of the magnetic flux quantum. This condition is realized by spontaneously generating a circulating supercurrent in the loop in such a way that its magnetic flux together with the external magnetic flux yields exactly one integer multiple of a flux quantum. (We have already shown a similar case in Fig. 5.2.)

This leads to an exactly periodic modulation of the shielding current in the loop depending on the external magnetic field. The circulating electrical shielding current now flows in addition to the external current, so that the electrical voltage drop along the loop arrangement is also periodically modulated. The voltage measurement still allows the resolution of a small fraction of a modulation period, resulting in a high sensitivity for magnetic field measurement. Today, SQUIDs are manufactured using thin film technology and integrated circuit technology.

Their high sensitivity as sensors for magnetic fields makes SQUIDs interesting for many applications. In medical diagnostics, new fields of application have developed that involve the magnetic fields generated by the electrical currents during cardiac activity and in the brain. This has led to the development of the new fields



R. P. Huebener, *History and Theory of Superconductors*, Springer essentials,
https://doi.org/10.1007/978-3-658-32380-6_12

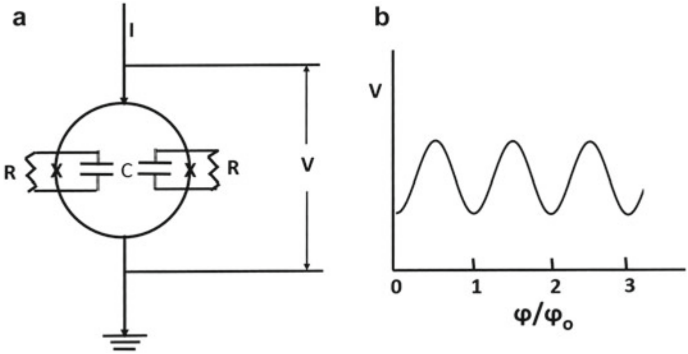


**Fig. 12.1** **a** Equivalent circuit diagram of the SQUID. The crosses (X) in the current loop indicate the Josephson contacts, which each contain a shunt resistor (R) and a shunt capacitance (C). **b** Voltage modulation at constant impressed current as a function of the magnetic flux $\varphi$ in the current loop in units of the flux quantum $\varphi_o$

of magnetocardiography and magnetoencephalography. In brain research today, devices with up to 275 SQUID channels are used. The channels with the individual sensors are arranged three-dimensionally around the head of the test person or patient. In Fig. 12.2, we show an example. In SQUID scanning microscopes, especially miniaturized SQUIDs are used. Their high magnetic field sensitivity combined with a spatial resolution of only a few µm allows the imaging of individual magnetic flux quanta in superconductors. An application of a SQUID scanning microscope is shown in Fig. 9.7 of Sect. 9.3. Further applications for SQUIDs can be found in nondestructive materials testing.

At present, small spin systems in nanoparticles are attracting particular attention. The latest development of these SQUID instruments is the production of ultra-small devices on sharp tips on the nano-scale (nano-SQUID-on-tip). By depositing superconducting lead or niobium on the tip of hollow quartz tubes, SQUID loops with an effective diameter of only 160 nm or even less than 100 nm can be achieved. An estimation shows that the signal of a single electron spin located 10 nm below a SQUID-on-tip loop can still be resolved with a spatial accuracy of about 20 nm.

Today, the Josephson effect has numerous applications in so-called *Josephson electronics*. The second Josephson Eq. (7.2) states that an electrical voltage drop at a Josephson contact is always associated with a high-frequency oscillation of the supercurrent between both electrodes of the contact. Here, a voltage

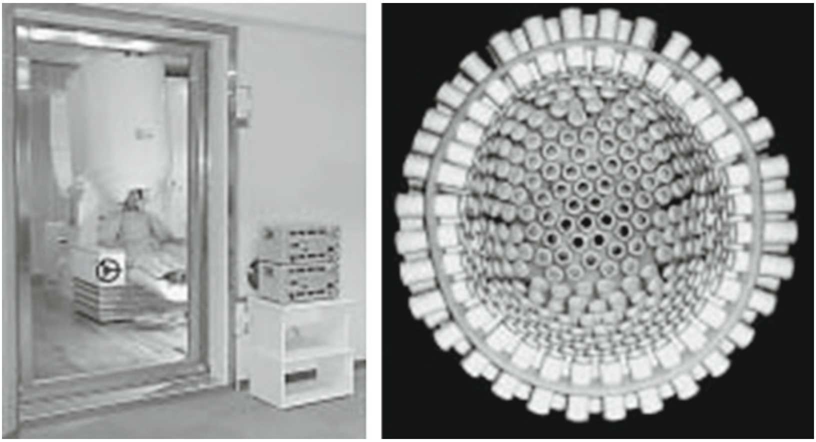

**Fig. 12.2** Magnetoencephalography. *Left*: Test subject with the helmet put over his head with the SQUID magnetic field sensors in a magnetically shielded room. *Right*: Interior view of a helmet with 151 SQUID sensors. (Photos: MEG International Services Ltd.)

of $10^{-3}$ V corresponds to an oscillation frequency of 483.6 GHz. If, on the other hand, a current-carrying Josephson contact is irradiated with a high-frequency electromagnetic wave, for example with a microwave, pronounced electrical voltage plateaus occur at the contact. The second Josephson equation determines the value of the voltage plateau by the frequency of the irradiated electromagnetic wave. Since frequencies can be measured very accurately, this quantum relationship between frequency and electrical voltage has been used since January 1, 1990 for the legal definition of the unit of electrical voltage by the state calibration offices. On the basis of this Josephson voltage standard, a voltage of 1 V corresponds to the frequency 483,597.9 GHz. In this way, the Josephson effect is part of the famous *quantum triangle* of current, voltage and resistance for the definition of electrical units of measurement.

In the case of high-temperature superconductors, the relatively high values of the critical temperature compared with those of classical superconductors in particular have given a great boost to the search for their technical applications. The possibility of using superconductivity already when cooled down to 77 K with liquid nitrogen is particularly attractive. In Sect. 9.3, we mentioned the fabrication of Josephson contacts and SQUIDs on bicrystal substrates in thin films of high temperature superconductors. This method is widely used today. High-frequency filters made of high-temperature superconducting layers are interesting because they have a greater frequency sharpness of the high-frequency channels so that significantly more channels can be accommodated within the available frequency band. For example, more than 10,000 base stations for mobile telephone traffic are already operated with this technology worldwide. Cooling down to about 70 K is done by so-called cryocoolers, which have been developed in recent years for reliable cooling and which can run maintenance-free for long periods of time.

## 12.2 Power Engineering

The applications of superconductivity in power engineering, for example, for magnet coils or cables, only became possible when new superconductor materials with higher values of the critical electric current density and the upper critical magnetic field $H_{C2}$ were discovered in the 1960s. The focus was then on the compounds NbTi with $T_C = 9.6$ K and $Nb_3Sn$ with $T_C = 18$ K. At that time, thin layers of the compound $Nb_3Ge$ reached the record value of the critical temperature of classical superconductors with $T_C = 23.2$ K. For industrial production, special drawing and extrusion processes as well as optimized annealing treatments and cold-working were quickly developed. The so-called "multifilamentary wires," which consist of many thin filaments of the superconductor material within a copper matrix, became famous. This technique guarantees certain stability in case of overload and at the same time provides sufficient pinning centers for anchoring the magnetic flux quanta in the superconductor material.

Superconducting magnetic coils are an important product today, especially for research. In Fig. 12.3, we show two examples. Large beam guiding magnets for particle accelerators and the associated particle detector systems are indispensable today. The "Large Hadron Collider" (LHC) at the European Nuclear Research Center (CERN) in Geneva has been in operation for several years as the world's largest particle accelerator based on superconductivity.

Another large-scale application of superconductivity is found in magnetically levitated trains. Recently, especially the Japanese JR-Maglev project has made good progress. In 2015, tests showed that a speed of over 600 km/h was achieved. Superconducting coils are mounted in the train, which generate magnetic fields above 5 T. Electrically well-conducting current loops are built into the track bed, in which strong eddy currents are generated when the train passes by. According to Lenz's rule, the magnetic field of the eddy currents causes a repulsive force on the field of the coils and thus the levitating force. Since this repulsion is only sufficiently strong above a certain minimum speed, the train must first run on wheels, which are retracted when this speed is reached.

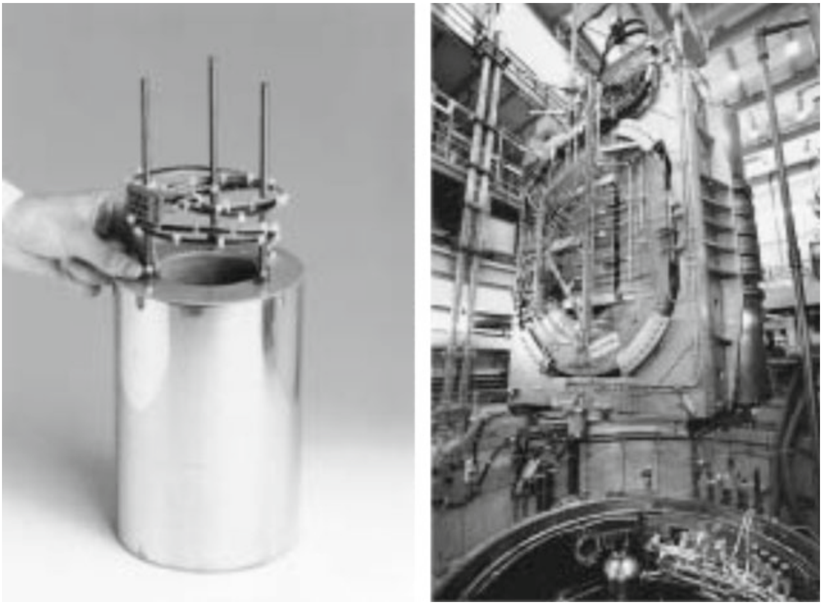

**Fig. 12.3** Superconducting magnet coils. **(Left)** Commercially available coil for research purposes. The coil is wound from niobium-titanium (NbTi) wire and can generate a magnetic field up to 9 T (about 1 million times the Earth's magnetic field). (Oxford.) **(Right)** Superconducting model coil with its test setup for a toroidal magnetic field when entering the cryogenic container of an experimental facility at the Karlsruhe Research Center (Forschungszentrum Karlsruhe). The experimental facility is used to develop the technology for magnetic plasma confinement during nuclear fusion. The external dimensions of the oval model coil are 2.55 m × 3.60 m × 0.58 m. During operation, an electric current of 80,000 amperes flows through the coil. The entire test assembly weighs 107 tons and shall be cooled to 4.5 K. The cryogenic container has a usable inside diameter of 4.3 m and a usable height of 6.6 m (Forschungszentrum Karlsruhe)

An important market for superconductivity technology has developed over the last 30 years due to the superconductive magnets used in magnetic resonance imaging. This was helped by the fact that at the beginning of the 1980s, the health authorities allowed magnetic resonance imaging for medical diagnostics. The annual turnover of the industry in this field today amounts to 2–3 billion EUR.

Superconducting energy transmission cables with classical superconductors have also been investigated since the 1970s in various pilot projects. Cooling with liquid helium was envisaged. Superconducting energy transmission cables are of particular interest where the usual overhead lines are not possible in conurbations.

Superconducting magnetic energy storage devices based on magnetic coils operated with direct current are an interesting technology for storing electrical energy. They can be useful for bridging short interruptions in the electrical energy supply. Finally, superconducting coils are indispensable in nuclear fusion to generate the high magnetic fields required for plasma confinement. The largest superconducting magnet systems are currently being developed for this long-term energy supply option.

In the field of high-current applications, intensive work is being done on the development of magnetic coils made of *high-temperature superconductors.* Furthermore, superconducting systems for electrical current limitation in power engineering are in a promising stage of development. These systems are intended to enable rapid interruption of the electrical current if overload threatens to cause damage to the electrical lines. A particularly interesting new development is currently (2015) in generators made of high-temperature superconductors for electrical power generation by wind energy. Their planned use would halve the weight of the generator located at the top of the mast compared to the previous equipment or double the power for the same weight.